The Effect upon Asteroid by the Neutron Radiation of Nuclear Explosion

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The problem of affecting upon an asteroid by the neutron radiation of nuclear explosion was considered. This effect was estimated depending on time, the altitude of explosion, energy spectrum, asteroid density and chemical composition and the angle of fall for two-dimensional parallel flow of absorbed energy of neutron radiation. To a first approximation, the temperature fields generated in asteroid by the neutron irradiation were obtained and compared with the appropriate temperature field generated by the x-radiation of nuclear explosion.

The Problem Statement

Nowadays concentration of energy in the nuclear explosives is the highest if compared with the other well-known sources of energy. This fact allows to consider nuclear explosives as the most promising means of effect upon the near-Earth-objects (NEO).

In the course of nuclear explosion a space object is exposed to different types of effects, intensity of which depends on the nuclear explosion yield, the distance to the space object, the object dimensions, the constituent materials and the nuclear explosive design.

The fraction of energy transferred to the space object at the explosion defines the scale of the effect. For a buried explosion this fraction is maximum [1,2,3], but to provide such explosion is a very complicated technical problem. It is technically much more easy to conduct a surface or stand-off explosion. In addition to the fraction of absorbed energy there is one more significant characteristic, the area of energy absorption or what kind of source of gasdynamic motion appears in the asteroid.

The motion of the asteroid ground in the surface and stand-off explosions is determined by the amount of energy, which is transferred to the asteroid material directly. The energy of the explosion is transferred to the ground in the form of X-radiation, neutron radiation and the impact of nuclear explosive vapors upon the surface of the asteroid. As it is shown in the papers [1,2,3] the fraction of energy transferred to the ground by X-radiation is about 6% of the total energy of explosion and the contribution of the vapor impact is about 2%. However, the effect of neutron radiation of the nuclear explosive which results in the ground heating is not considered in these papers. In this paper we provide data allowing to estimate the heating effect. Note, that some issues of neutron effect upon the asteroids are examined in the papers [5,6].

The following types of the nuclear explosions with the yield of 1MT are under consideration:

- surface explosions (1m above the surface);
- stand-off explosions at the altitude of 1.5 m, 5 m, 10 m;
- distant explosions, when the neutron flux affecting the surface can be considered as two-dimensional parallel.

Asteroid is considered to be stony with two types of chemical composition: SiO_2 and $O_{0.569}Si_{0.167}Fe_{0.06}Mg_{0.139}Al_{0.065}$. The terrestrial rocks can play the role of analogs. The asteroid density is assumed to be 1, 2 and 2.7 g/cm^3.

In general, neutrons carry a small fraction of the explosion energy. Thus, in the process of fission the kinetic energy of neutrons is about 2.5% of total released energy. In the process of fusion the fraction of the kinetic energy of neutrons is much higher (it reaches 80% of total energy in the D-T process). However, in the current thermonuclear explosives about a half of total energy is produced in the process of fission. Moreover, the conditions of thermonuclear fuel combustion are provided by surrounding it with structurial materials of large mass. This leads to the moderation of neutrons and their absorption by the structure components and, as a result, to the distortion of spectrum of the emitted neutrons towards its softening. Ultimately, the main fraction of energy is released by the current thermonuclear explosives of gross yield in the form of x-radiation.

We assume, that during explosion having yield E (MT) the $E_f=\eta_f E$ fraction of energy is released due to fission and the $E_t=\eta_t E$ fraction is released due to thermonuclear reactions. We ignore the neutron spectrum distortion occurring while the neutrons pass the layers of the nuclear explosive structure. The λ coefficient expresses the absorption scale.

Estimate the number of neutrons produced in the process of fission. Each fission releases $\varepsilon_f \approx 180$ MeV$\approx 2.9 \cdot 10^{-14}$ KJ and produces ν neutrons. Considering the number of neutrons absorbed in the chain fission reaction, the total number of produced neutrons is the following:

$$N_{f0}=(E_f/\varepsilon_f)\cdot(\nu-1)\approx\eta_f(\nu-1)\cdot E\cdot 1.4\cdot 10^{26}$$

For $\nu\approx 3$ the number of produced neutrons is $N_f\approx\eta_f E\cdot 3\cdot 10^{26}$. Assuming, that only $_f$ fraction of produced neutrons leaves the nuclear explosive, the total number of neutrons of fission spectrum, reaching the asteroid surface, is

$$N_f\approx\lambda_f\eta_f E\cdot 3\cdot 10^{26}.$$

Similarly, the number of neutrons produced in the fusion reactions is the following:

$$N_{t0}=(E_t/\varepsilon_t)\approx\eta_t E\cdot 1.4\cdot 10^{27}, \text{ where } \varepsilon_t=17 \text{ MeV}\approx 3\cdot 10^{-15} \text{ KJ}.$$

Assuming, that only λ_t fraction of produced neutrons leaves the nuclear explosive, the total number of thermonuclear neutrons, is the following:

$$N_t = \lambda_t\cdot\eta_t\cdot E\cdot 1.4\cdot 10^{27}.$$

Thus, the following number of neutrons comes off the nuclear explosive:

$$N\approx\lambda_f\eta_f E\cdot 3\cdot 10^{26}+\lambda_t\cdot\eta_t\cdot E\cdot 1.4\cdot 10^{27}.$$

To estimate the energy transferred to the asteroid by neutron radiation of the current thermonuclear charge it is sufficient to calculate separately the energy of thermonuclear and fission neutrons and substitute the appropriate η_f, λ_f, η_t, λ_t coefficients.

The Surface Explosion. Comparison with X-radiation

The energy of neutron radiation absorbed by the asteroid materials was calculated by the method of Monte-Carlo [4]. Computed were two problems in the following statement. Asteroid was simulated by the infinite semispace. The asteroid material was modeled by silicon oxide SiO_2 with the density of 2.7 g/cm^3. Instantaneous point isotropic neutron source was located at the altitude of 1m. In the first problem fission neutrons were considered. In the second problem neutrons had the energy of 14 MeV.

Calculation results of the first problem are given for E=1 MT, $\eta_f=1$, $\lambda_f=1$. Time-dependence of energy (in KT) absorbed by the asteroid material is presented in Figure 2.1. One can see that characteristic time of energy absorption is about ≈ 0.2 µs. In this case the fraction of absorbed energy is a bit greater than 0.5% of the total explosion energy and that is an order of magnitude less than for x-radiation.

The similar dependencies were obtained for the second problem. Figure 2.2 presents the results for $\eta_t=1$, $\lambda_t=1$. In this case the fraction of absorbed energy is $\approx$20% and characteristic time of absorption is 0.1 µs.

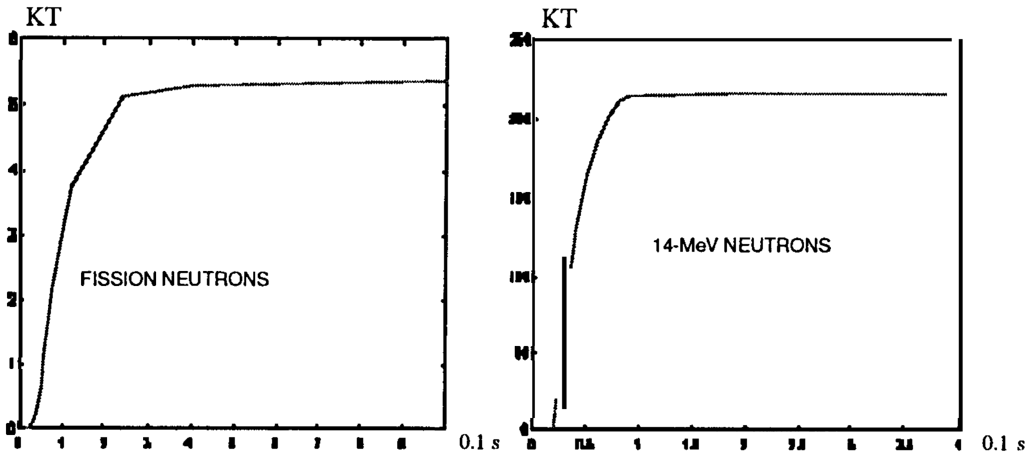

Fig.2.1,2. Time dependence of the absorbed energy fraction.

As mentioned above, for the current thermonuclear charges the fraction of absorbed energy, which neutron radiation transfers to the asteroid material, can be estimated by the simple superposition of the mentioned results with substitution of appropriate η_f, λ_f, η_t, λ_t coefficients.

The results presented lead to the obvious fact, that the fraction of energy absorbed by the asteroid material in the surface nuclear explosion can be rather significant if the thermonuclear explosives with the increased release of 14 MeV neutrons are used.

Since both the fraction of absorbed energy and the area of energy absorption are the important parameters, let us consider gasdynamic sources appeared due to 14 MeV neutrons (their effect is greater than that of the fission neutrons) and x-radiation. The temperature profiles, appearing due to x-radiation (2 KeV) and 14 MeV neutrons released by an 1 MT yield explosion at the level of 1 KeV, are shown in Fig. 2.3. It is obvious, that 14 MeV neutron radiation generates more effective gasdynamic source since the lens of heating is large in both longitudinal and cross directions.

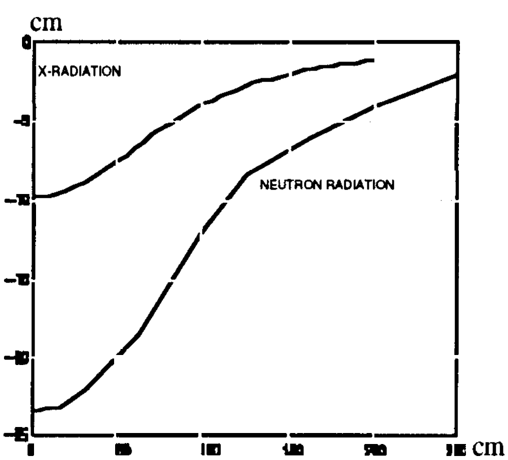

Fig.2.3. Heating lens for X-rays and 14-MeV neutron radiation at the level of 1 KeV.

The Effect of the Explosion Elevation Above the Asteroid Surface

It is a difficult technical problem to conduct a surface explosion at the typical velocities of a space interceptor and NEO. That is one of the reasons for some authors, for example [5,6], to propose above-surface explosions in order to transfer the maximum momentum and to mitigate the effect. A series of calculations was performed to estimate the dependence of a fraction of energy absorbed by an asteroid and of gasdynamic source creation on an explosion elevation. As in the previous paragraph asteroid was simulated by the infinite semispace. Asteroid's material composition is the following $O_{0.569}Si_{0.167}Fe_{0.06}Mg_{0.139}Al_{0.065}$ with the density of 2 g/cm^3. The altitude of the explosion was various: 1.5 m, 5 m, 10 m. Both spectra of fission and 14 MeV neutrons were studied. The results of calculations are presented in Table 3.1.

Table 3.1.

Elevation m	Spectrum	Absorbed Energy KT	T_{max} KeV
1.5	14 MeV	226	1.86
5.0	14 MeV	227	0.24
10.0	14 MeV	228	0.06
1.5	fission	6	0.07
5.0	fission	6	0.06
10.0	fission	6	0.0014

The data given in Table 3.1 show that the fraction of absorbed energy within the limits of calculation error does not practically depend on the explosion altitude. Nevertheless, the effects upon an asteroid are different, since the lenses of heating which are the areas where asteroid matter is heated to a high temperature differ grossly: the higher the elevation, the larger is the diameter and the lower are the temperature and width. Figures 3.1 and 3.2 show the temperature profiles in the lens of heating, illustrating this effect (for 14 MeV neutrons and fission neutrons, respectively). The plots demonstrate that when the explosion altitude increases the heated area becomes less deep and more flat. Comparing Figs. 3.1 and 3.2 one can see that gasdynamic source produced by neutron radiation with fission spectrum is less effective. Thus, for approximately the same areas of heating the temperature in the case of thermonuclear neutrons is 20 times as much as in the case of fission neutrons.

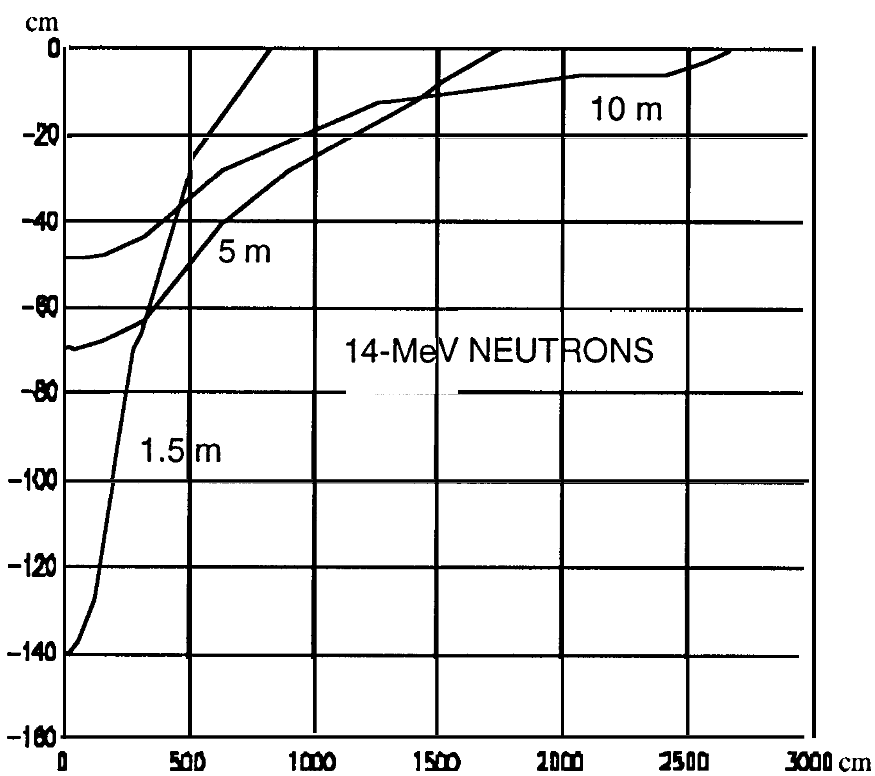

Fig.3.1. Shapes of the heating lenses for the different explosion altitudes at the level of T=0.01 KeV.

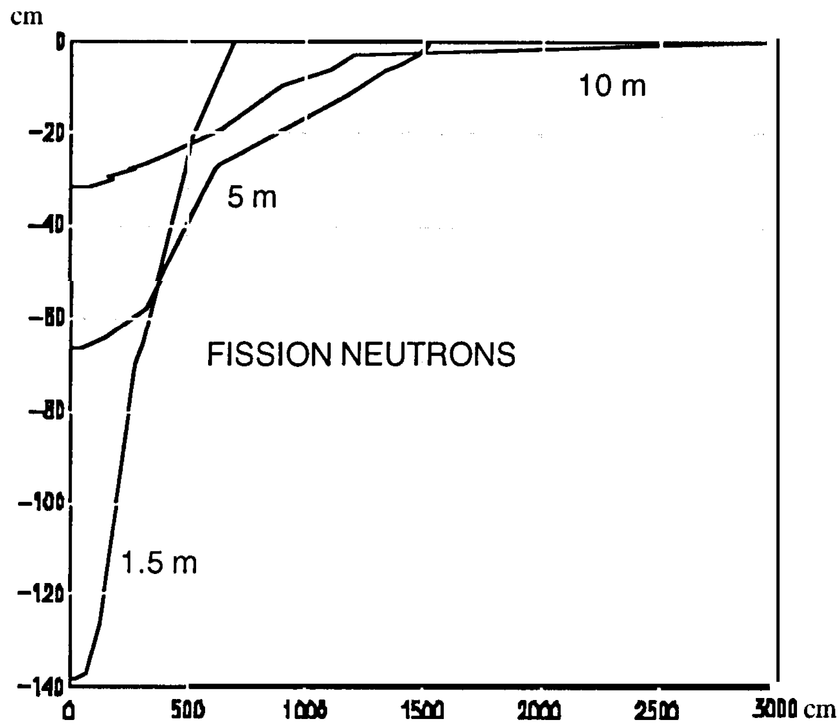

Fig.3.2. Shapes of the heating lensese for the different explosion altitudes at the level of T=0.0005 KeV.

The Effect of the Asteroid Density

Nowadays there is a significant uncertainty in the physical-chemical properties of the NEOs, in particular, in the density. For a subsurface explosion this issue is not a matter of principle. Situation is different for the surface and above-surface explosions, since creation of a gasdynamic source and, as a consequence, the momentum transferred to NEO are determined by the density to a considerable extent. Therefore, performed were the calculations of the problem described in paragraph 3 for various asteroid densities and the explosion altitude of 1.5 m (both for fission and 14 MeV neutrons). The results are given in Table 4.1.

Table 4.1

Density, g/cm3	Spectrum	Absorbed Energy KT
1.0	14 MeV	222
2.0	14 MeV	226
2.7	14 MeV	226
1.0	fission	6.1
2.0	fission	6.2
2.7	fission	6.3

Table 4.1 shows that within the limits of calculation error the fraction of absorbed energy does not depend upon the density of asteroid matter. The difference is in the gasdynamic source. Figures 4.1 and 4.2 present the levels of temperatures produced by 14 MeV and fission neutrons for different densities. It follows from the plots, that when the ground density decreases the dimensions of the lens of heating increases, in particular, the depth and the cross dimensions for the same levels of temperature.

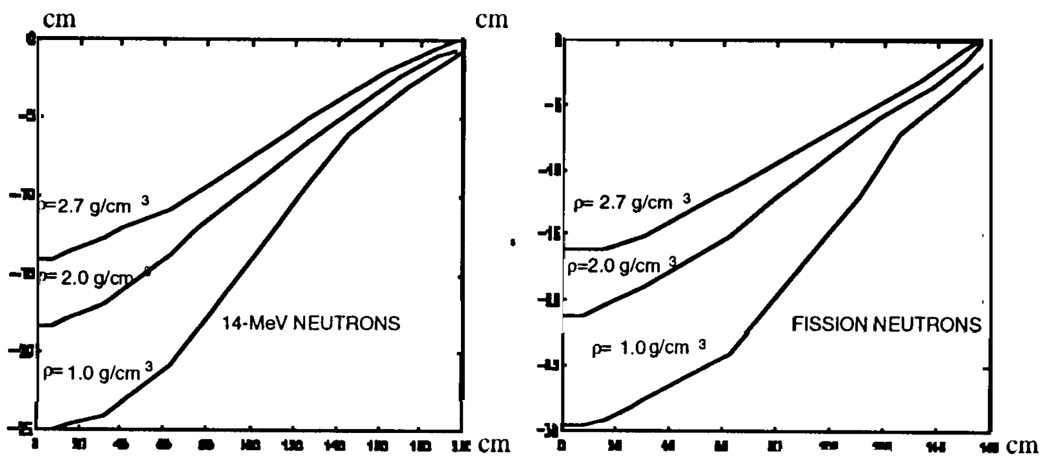

Fig.4.1,4.2. Shapes of the heating lenses for different densities at 1 KeV level for 14 MeV neutrons and at 0.03 KeV for fission neutrons.

The Effect of the Asteroid Chemical Composition

Evidently, the chemical composition of an asteroid should somehow influence both the fraction of absorbed energy and the temperature within the lens of heating. Consequently, calculations were performed related to the explosion at the elevation of 1.5 m for the asteroids with the density of 2.7 g/cm^3 and various chemical compositions. The results obtained are presented in Table 5.1.

Table.5.1

Composition	Spectrum	Absorbed Energy, kT
$O_{0.569}Si_{0.167}Fe_{0.06}Mg_{0.139}Al_{0.065}$	14 MeV	226
SiO_2	14 MeV	218
$O_{0.569}Si_{0.167}Fe_{0.06}Mg_{0.139}Al_{0.065}$	fission	6.3
SiO_2	fission	5.5

Table 5.1 argues, that the fraction of absorbed energy depends on the asteroid composition, the deviation for fission neutrons reaching 10% and for thermonuclear 3.7%. Note, that the discrepancy between considered compositions is not of a fundamental nature. This proves that in order to perform the exact calculations of the effect it is necessary to know chemical composition with reasonable accuracy.

The Effect of Two-Dimensional Parallel Neutron Flux

Papers [5,6] state that there is an optimal explosion distance from an asteroid surface determined by the value of transferred momentum. This distance is about 40% of an asteroid radius. At such distances the neutron flux affecting the asteroid can be considered as two-dimensional parallel neutron flux at any local point, including the case when the asteroid has irregular shape. The fraction of absorbed energy and temperature profiles with respect to the depth were calculated for the asteroid with the density of 2.0 g/cm^3 and chemical composition $O_{0.569}Si_{0.167}Fe_{0.06}Mg_{0.139}Al_{0.065}$ exposed to two-dimensional parallel neutron flux incident at some angle to the asteroid surface, which is simulated by the semi-infinite medium. Results were reduced to the flow of 1 kT/m^2. Figures 6.1 and 6.2 show the fraction of absorbed energy versus the incident angle for 14 MeV and fission neutrons, respectively. The plots argue that the fraction of absorbed energy can be well described by the law of cosine: $E_{abs} \sim \cos\theta$.

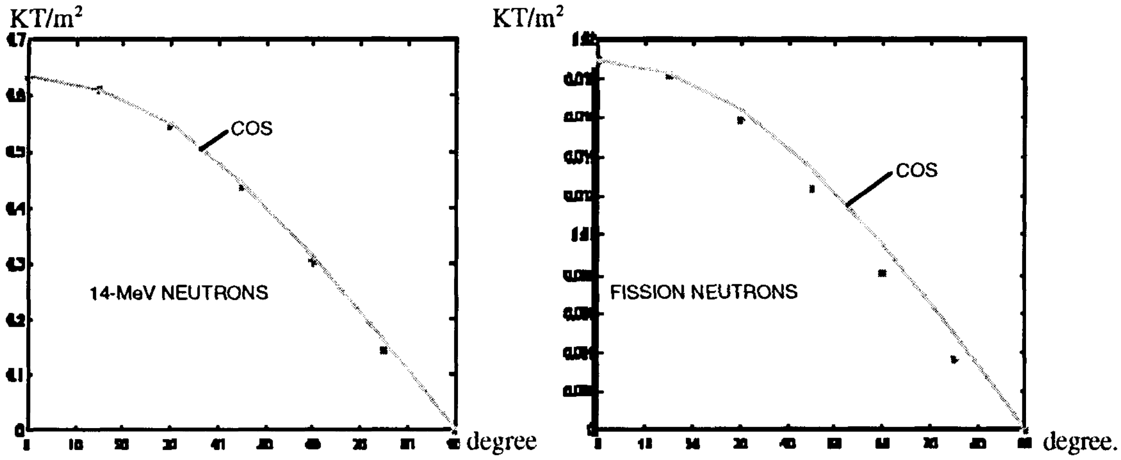

Fig.6.1,2.Dependence of absorbed energy fraction on incident angle.

The temperature profiles with respect to the depth, appearing in NEO are shown in Figures 6.3, 6.4. It follows from the plot analysis that the temperature at the asteroid surface depends only weakly on the incident angle, although the larger the angle, the greater decreases the temperature with the depth increase.

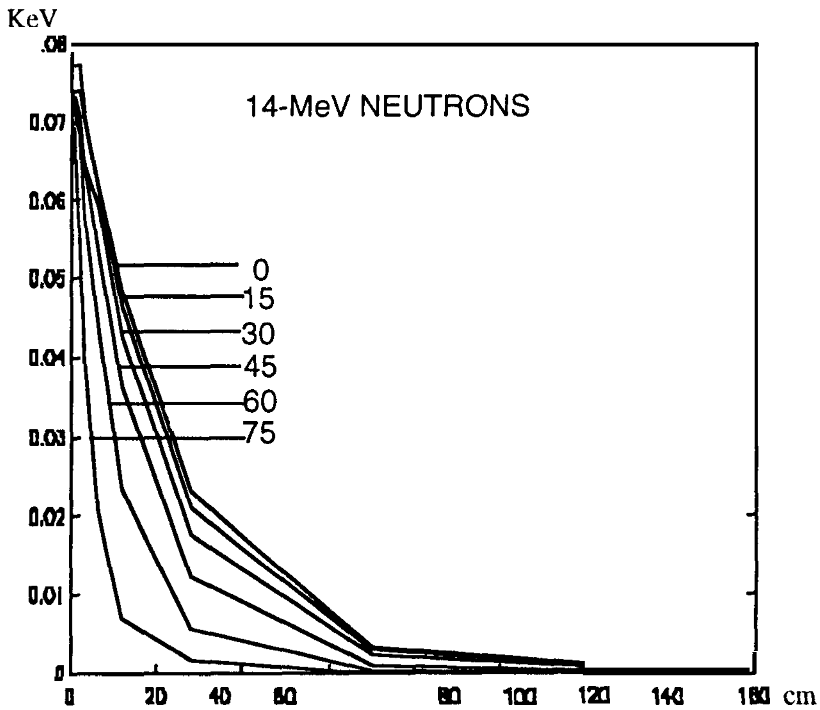

Fig.6.3. Dependence of temperature on depth for different incident angles.

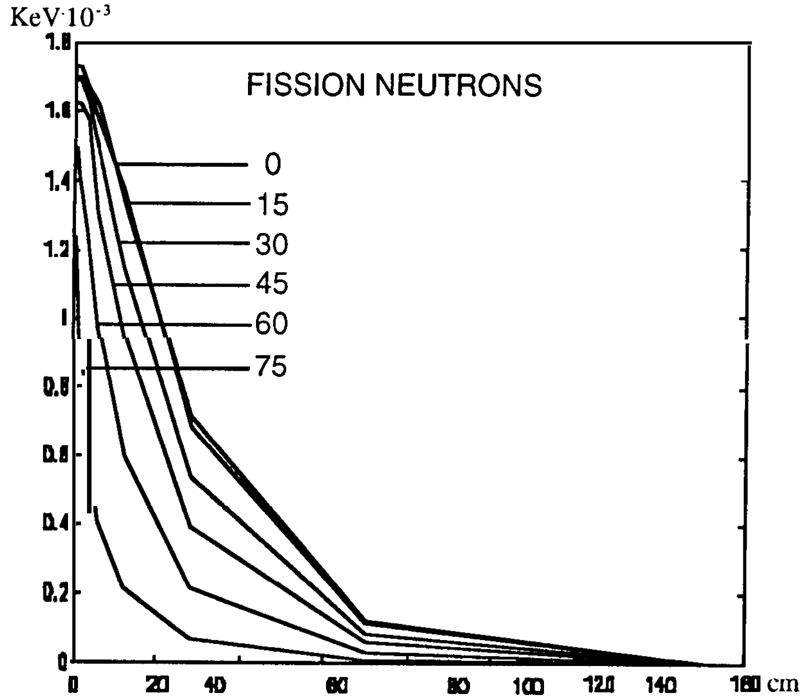

Fig.6.4. Dependence of temperature on depth for different incident angles.

Results and Discussion

We would like to comment the results obtained.

1. Since, in general, the surface and above-surface explosions are extremely complicated phenomena, all the calculations were performed for the simplified models. To describe the effect produced by neutrons correctly it is necessary to take into account X-radiation. Since the velocity of photons is considerably higher than that of neutrons, the phenomenon develops in the following way:

A. At first, the asteroid material is heated by X-radiation, then its scattering begins.

B. The neutron radiation comes with some delay (depending on the altitude of the explosion). The separation of neutrons according to spectrum takes place in the case of the above-surface explosion (for the surface one this fact can be ignored). !4 MeV neutrons are the first to come and they are followed by the rest (v-$E^{1/2}$). In a surface explosion thermonuclear neutrons impact into an 'undisturbed' asteroid, but in the case of above-surface explosion they are at first to pass through a dilute (rarefied) cloud of the ejected ground and only then they can impact into the asteroid material, which have been disturbed by energy deposition of the preceeding neutrons and other factors as well. Due to passing through the cloud the neutrons scatter, slow down and are taken away by the cloud material and all these lead to the reduction of neutron effectiveness. Consequently, the actual fraction of energy absorbed by the asteroid is lower than the value, calculated by the authors of this paper. Quantitative estimate of this effect requires further examination and development.

2. The effect of fission neutrons compared with that of x-radiation (0.5% versus 6%) can be ignored even without regard for the above-mentioned factor. This fact can be considered as proved.

3. Within the model the effectiveness of 14 MeV neutrons is much higher than of x-radiation, namely 20% versus 6%. However, the following aspects were not considered while modeling:

A. For a surface explosion of 1 MT yield the thermonuclear neutron radiation leads to high temperature of 2 KeV within the lens of heating. For such temperature radiation contributes to energy the most. Therefore the fraction of absorbed energy is reradiated until the temperature decreases to 1 KeV and, as a result, absorbed energy decreases

B. As it was already mentioned, for the above-surface explosion the neutron interaction with the ground ejected by x-radiation decreases and this leads to the decrease of absorbed energy.

Consideration of A. and B. factors can show that there exists the optimal altitude and/or yield of an explosion when addressing the asteroid with specific physical-chemical properties.

C. The softening of spectrum and the decrease of the number of neutrons due to their interaction with the nuclear explosive design lead to reduction of absorbed energy.

Above mentioned aspects should be considered in detail and they are beyond the scope of this paper. But these factors can equalize the effectiveness of 14 MeV neutrons and x-radiation.

Conclusions

1. The effect of neutron radiation of fission spectrum on an asteroid can be ignored, if compared with x-radiation produced by an explosion of the same yield.

2. 14 MeV neutron radiation in 'zero' approximation is more effective than x-radiation of an explosion of the same yield. But their effectiveness can appear to be equal, if the physical essence of an explosion is examined in detail.

3. Prediction of the asteroid behavior after the impact of neutron radiation requires reasonably accurate knowledge of the physical and chemical properties of the asteroid (such as shape, density, material composition, etc.), since gasdynamic source formation depends upon them.

4. The results obtained can be used as the initial data for determining the momentum, which NEO acquires due to the effect of neutron radiation of the nuclear explosion.

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